AMTD: update of engineering specifications derived from science requirements for future UVOIR space telescopes

Mirror Technology Days in the Government 2014
Albuquerque
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Summary

Summary

In AMTD-1 2013 paper we:

- Discussed the flow down to Telescope Aperture Diameter from Science Requirements, including:
  - Habitable Zone Resolution Requirement
  - Signal to Noise Requirement
  - η_{EARTH}
  - Exo-Zodi Resolution Requirement
- Developed a PSD tool for flowing the Diffraction Limit Requirement to a Surface Wavefront Error Specification.
- Proposed a Wavefront Error Stability Specification.
- Considered Wavefront Stability issues of a Segmented Mirror
- And, reviewed Launch Vehicle and Environmental Constraints

Stahl, H. Philip, Marc Postman and W. Scott Smith, “Engineering specifications for large aperture UVO space telescopes derived from science requirements”, Proc. SPIE 8860, 2013, DOI: 10.1117/12.2024480

Summary

In AMTD-2 we continue to update and refine our findings.

In this paper we:

- Refine the Telescope Aperture Diameter flow down from Science Requirements based on a new paper by Stark et. al.
- Discuss the impact of Launch Vehicle Constraints on implementing the desired aperture diameter.
- Review the Surface Wavefront Error Specification.
- Define a Wavefront Error Stability Specification.
- Discuss the scaling of Aperture Size and Stiffness

Maximizing the ExoEarth Candidate Yield from a Future Direct Imaging Mission, Stark, C. C., Roberge, A., Mandell, A., & Robinson, T. 2014, ApJ, submitted

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Introduction

Future UVOIR Space Telescope

Astro2010 Decadal Study recommended technology development (page 7-17) for a potential future:

- Exoplanet Mission (New-Worlds Explorer)
- UVOIR Space Telescope (4 meter or larger)

2012 NASA Space Technology Roadmaps & Priorities: Top Technical Challenge C2 recommended:

- New Astronomical Telescopes that enable discovery of habitable planets, facilitate advances in solar physics, and enable the study of faint structures around bright objects …

2014 Enduring Quests Daring Visions recommended:

- LUVOIR Surveyor with sensitivity to locate the bulk of planets in the solar neighborhood and reveal the details of their atmospheres.

AMTD

Most future space telescope missions require mirror technology.

This technology must enable missions capable of both general astrophysics & ultra-high contrast observations of exoplanets.

Advanced Mirror Technology Development (AMTD) is a multi-year effort to systematically mature to TRL-6 the critical technologies needed to produce 4-m or larger flight-qualified UVOIR mirrors by 2018 so that a viable mission can be considered by the 2020 Decadal Review.

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Multiple Technology Paths

Just as JWST's architecture was driven by launch vehicle, future mission's architectures (mono, segment or interferometric) will depend on capacities of future launch vehicles (and budget).

Since we cannot predict future, we must prepare for all futures.

To provide science community with options, we must pursue multiple technology paths: monolithic AND segmented.

All potential UVOIR mission architectures (monolithic, segmented or interferometric) share similar mirror needs:

- Very Smooth Surfaces — < 10 nm rms
- Thermal Stability — Low CTE Material
- Mechanical Stability — High Stiffness Mirror Substrates

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Engineering Specification

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Engineering Specification

To meet our goals, we need to derive engineering specifications for future monolithic or segmented space telescope based on science needs & implementation constraints.

We use a science-driven systems engineering approach:

Science Requirements → Engineering Specifications

Science & Engineering work collaboratively to insure that we mature technologies required to enable highest priority science AND result in a high-performance low-cost low-risk system.

STOP (structural, thermal, optical performance) models are used to help predict on-orbit performance & assist in trade studies.

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Summary

Science Requirements, Launch Vehicle & Programmatic Constraints define different Engineering Specifications

Science Requirements →	Engineering Specifications
Exoplanet	
Sample Size	Telescope Diameter
Spectral Resolution	Telescope Diameter
Contrast	Mid/High Spatial Error
Contrast	WFE Stability
Star Size	Line of Sight Stability
General Astrophysics	
Diffraction Limit	Wavefront Error (Low/Mid)
Spatial Resolution	Telescope Diameter
Launch Vehicle	
Up-Mass Capacity	Areal Mass
Fairing Size	Architecture (monolithic/segmented)
Programmatic	
Budget Size	Areal Cost

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Disclaimer

The purpose of this effort is NOT to design a specific telescope for a specific mission or to work with a specific instrument.

We are <u>not</u> producing an optical design or prescription.

We <u>are</u> producing a set of primary mirror engineering specifications which will enable the on-orbit telescope performance required to enable the desired science.

Our philosophy is to define a set of specifications which 'envelop' the most demanding requirements of all potential science. If the PM meets these specifications, it should work with most potential science instrument.

Future is to integrate these PM specifications into a telescope.

Also, right now, Coatings are out of scope.

And, this presentation is a sub-set of our work.

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Science Requirements

Requirements for a large UVOIR space telescope are derived directly from fundamental Science Questions (2010)

Table 2.1: Science Flow-down Requirements for a Large UVOIR Space Telescope

Science Question	Science Requirements	Measurements Needed	Requirements
Is there life elsewhere in Galaxy?	Detect at least 10 Earth-like Planets in HZ with 95% confidence.	High contrast (ΔMag > 25 mag) SNR=10 broadband (R = 5) imaging with IWA ~40 mas for ~100 stars out to ~20 parsecs.	≥ 8 meter aperture Stable 10^{-10} starlight suppression ~0.1 nm stable WFE per 2 hr ~1.3 to 1.6 mas pointing stability
	Detect presence of habitability and bio-signatures in the spectra of Earth-like HZ planets	High contrast (ΔMag > 25 mag) SNR=10 low-resolution (R=70-100) spectroscopy with an IWA ~ 40 mas; spectral range 0.3 – 2.5 microns; Exposure times <500 ksec	
What are star formation histories of galaxies?	Determine ages (~1 Gyr) and metallicities (~0.2 dex) of stellar populations over a broad range of galactic environments.	Color-magnitude diagrams of solar analog stars (Vmag~35 at 10 Mpc) in spiral, lenticular & elliptical galaxies using broadband imaging	≥ 8 meter aperture Symmetric PSF 500 nm diffraction limit 1.3 to 1.6 mas pointing stability
What are kinematic properties of Dark Matter	Determine mean mass density profile of high M/L dwarf Spheroidal Galaxies	0.1 mas resolution for proper motion of ~200 stars per galaxy accurate to ~20 μas/yr at 50 kpc	
How do galaxies & IGM interact and affect galaxy evolution?	Map properties & kinematics of intergalactic medium over contiguous sky regions at high spatial sampling to ~10 Mpc.	SNR = 20 high resolution UV spectroscopy (R = 20,000) of quasars down to FUV mag = 24, survey wide areas in < 2 weeks	≥ 4 meter aperture 500 nm diffraction limit Sensitivity down to 100 nm wavelength.
How do stars & planets interact with interstellar medium?	Measure UV Ly-alpha absorption due to Hydrogen "walls" from our heliosphere and astrospheres of nearby stars	High dynamic range, very high spectral resolution (R = 100,000) UV spectroscopy with SNR = 100 for V = 14 mag stars	
How did outer solar system planets form & evolve?	UV spectroscopy of full disks of solar system bodies beyond 3 AU from Earth	SNR = 20 - 50 at spectral resolution of R ~10,000 in FUV for 20 AB mag	

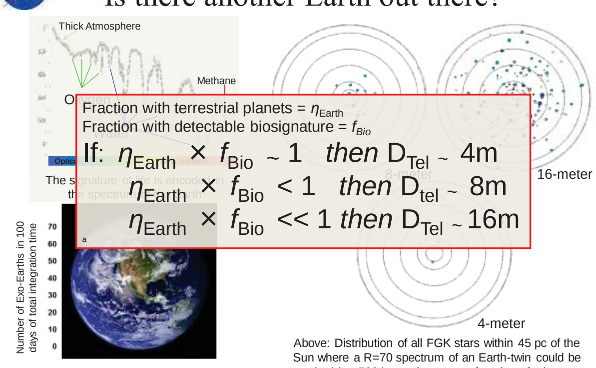
Exoplanet Measurement Capability

Exoplanet characterization places the most challenging demands on a future UVOIR space telescope.

Science Question	Science Requirements	Measurements Needed
Is there life elsewhere in the Galaxy?	Detect at least 10 Earth-like Planets in HZ with 95% confidence if $\eta_{EARTH} = 0.15$	High contrast (ΔMag>25 mag) SNR=10 broadband (R=5) imaging with IWA ~ 40 mas for ~100 target stars.
	Detect the presence of habitability and bio-signatures in the spectra of Earth-like HZ planets	High contrast (ΔMag>25 mag) SNR=10 low-resolution (R=70-100) spectroscopy with an IWA ~ 40 mas. Exposure times <500 ksec.

Must be able to resolved a sufficient number of planets in their star's habitable zone AND obtain an R = 70 spectra at 760 nm (molecular oxygen line is key biomarker for life).

"Is there another Earth out there?"



Fraction with terrestrial planets = η_{Earth}

Fraction with detectable biosignature = f_{Bio}

If: $\eta_{Earth} \times f_{Bio} \sim 1$ *then* $D_{Tel} \sim$ 4m

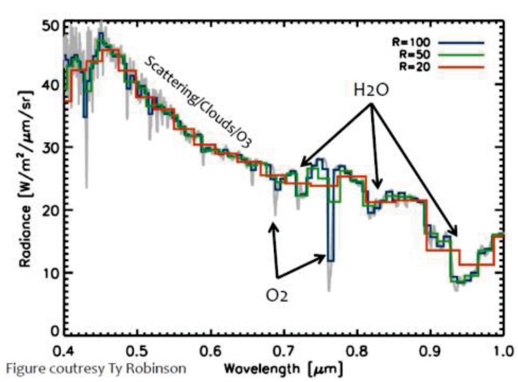
$\eta_{Earth} \times f_{Bio} < 1$ *then* $D_{tel} \sim$ 8m

$\eta_{Earth} \times f_{Bio} << 1$ *then* $D_{Tel} \sim$ 16m

Above: Distribution of all FGK stars within 45 pc of the Sun where a R=70 spectrum of an Earth-twin could be acquired in <500 ksec *shown as a function of telescope aperture*. Assumes eta_Earth = 0.1 and IWA = 2λ/D.

Beyond HST: The Universe in High-Definition – UVOIR Space Astronomy in 2030, Marc Postman & Julianne Dalcanton, Science with HST IV Meeting, Rome, Italy, March 18, 2014

Importance of Spectral Resolution



AT-LAST Wavelength Range for Life Detection, Shawn Domagal-Goldman

Aperture Size Specification

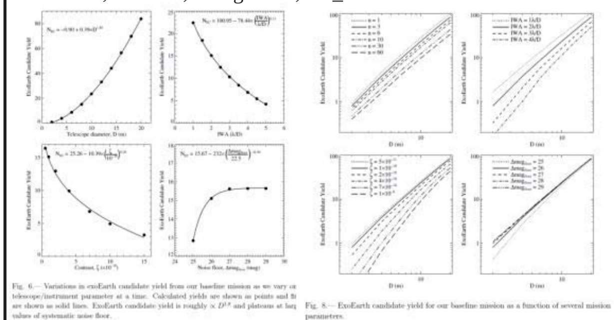
Aperture Size

Telescope Aperture Size is driven by:

- Number of Earth Candidates required for Characterization
- Characterization Spectral Resolution Signal to Noise
- Angular Resolution

Maximizing Exo-Earth Candidates

Per Stark et al., # of candidates depends on Aperture Diameter, IWA, Contrast, ΔMagnitude, Eta_Earth and Exo-Zodi



Maximizing the ExoEarth Candidate Yield from a Future Direct Imaging Mission, Stark, C. C., Roberge, A., Mandell, A., & Robinson, T. 2014, ApJ, submitted

Detect & Characterize versus Aperture Size

Number of Candidate Exo-Earths that can be Detected and Characterized to R = 70 with SNR = 10 in approx 1.5 years of mission observation time as a function of Aperture.

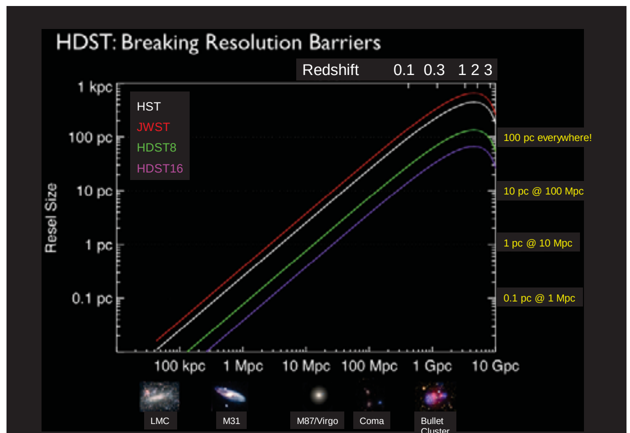
Aperture Diameter	IWA = 2 λ/D	IWA = 1 λ/D
4 meter	4	6
8 meter	15	22
12 meter	33	44
16 meter	56	77

Assuming:

Eta_Earth = 10% (increasing to 20% would double #)

Exo-Zodi = 3 (increasing to 30 would halve #)

Maximizing the ExoEarth Candidate Yield from a Future Direct Imaging Mission, Stark, C. C., Roberge, A., Mandell, A., & Robinson, T. 2014, ApJ, submitted



Beyond HST: The Universe in High-Definition – UVOIR Space Astronomy in 2030, Marc Postman & Julianne Dalcanton, Science with HST IV Meeting, Rome, Italy, March 18, 2014

Aperture Size Recommendation

Based on the analysis, the Science Advisory Team recommends a space telescope in the range of 8 meters to 16 meters.

Telescope Diameter	Architecture
8 meter	Monolithic
8 meter	Segmented
> 8 meter	Segmented

An SLS with a 10-meter fairing can launch an 8-meter class monolithic mirror.

A segmented aperture is required for:

any launch vehicle with a 5 m fairing (EELV or SLS Block 1)

any telescope aperture larger than 8-meters

Segmented Mirror Architectures

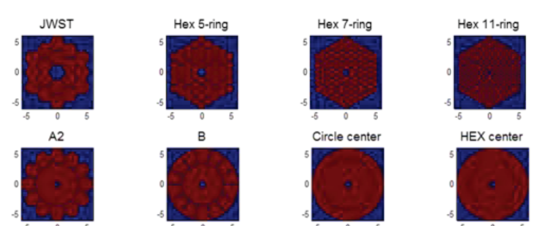
Two architectures are under consideration

- Hex Segment Architecture (similar to JWST or Keck or TMT)
- Center and Petals (similar to LAMP or ALOT)

Center and Petals can easily produce apertures from 10 to 14 m

6-m center with 2 to 4 m tall identical petals gives 10 to 14 meters

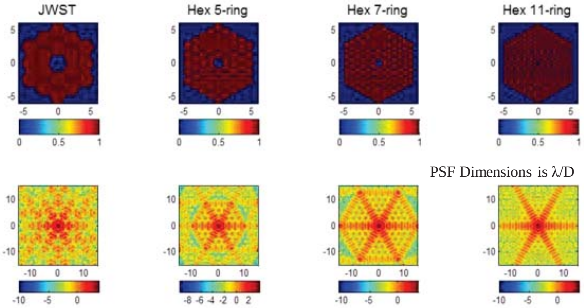
8-m center with 1 to 3 m tall identical petals gives 10 to 14 meters



Segmentation Point Spread Function

Hex Segmentation is similar to JWST, Keck, TMT or ELT.

PSF is structured and depends on segment size.

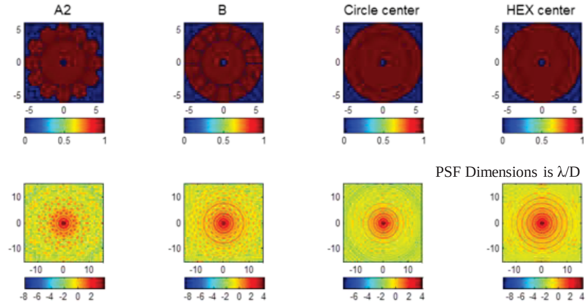


PSF Dimensions is λ/D

Segmentation Point Spread Function

Petal Segmentation is similar to LAMP or ALOT.

PSF is symmetric and depends on sizes of center and petals.



PSF Dimensions is λ/D

Areal Density

Independent of Architecture, Areal Density is constrained by launch vehicle up-mass capacity (single launch only).

Launch Vehicle	SEL2 Payload Mass [kg]	Primary Mirror Assembly [kg]	Aperture [m]	Areal Density [kg/m2]
JWST	6600	1600	6.5	64
Delta IVH	10,000	2500	8	50
			12	23
			14	16
			16	12
Falcon 9H	15,000	5000	8	100
			12	45
			14	32
			16	25
SLS Block 1	30,000	15,000	8	300
			12	135
			14	100
			16	75
SLS Block 2	60,000	30,000	8	600
			12	270
			14	200
			16	150

Wavefront & Surface Figure Error Specification

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Wavefront Error

Total system wavefront error (WFE) is driven by:

- 500 nm Diffraction Limited Performance
- Dark Hole Speckle

Exoplanet science driven specifications include:

- Line of Sight Pointing Stability
- Total Wavefront Error Stability

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WFE vs 500 nm Diffraction Limit

Total system WFE is derived from PSF requirement using Diameter, Strehl ratio (S) & wavelength (λ):

$$\text{PSF FWHM (mas)} = (0.2063 / S) * (\lambda(\text{nm}) / D(\text{meters}))$$
$$S \sim \exp(-(2\pi * \text{WFE}/\lambda)^2)$$
$$\text{WFE} = (\lambda/2\pi) * \text{sqrt}(-\ln S)$$

Diffraction limited performance requires S ~ 0.80.

At λ = 500 nm, this <u>requires total system WFE of ~38 nm</u>.

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Primary Mirror Total Surface Figure Requirement

Primary Mirror requirements are derived by flowing System Level diffraction limited and pointing stability requirements to major observatory elements:

- **Observatory** *40 nm rms*
  - **Instruments** *15 nm rms*
  - **Telescope** *36 nm rms*
  - **Pointing Control** *10 nm rms*

Then flowing Telescope Requirements to major Sub-Systems

- **Telescope** *36 nm rms*
  - **PMA** *20 nm rms*
  - **SMA** *16 nm rms*
  - **Stability** *20 nm rms*
  - **Assemble, Align** *16 nm rms*

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Primary Mirror Total Surface Figure Requirement

Then flowing major Sub-Systems Requirements into Manufacturing Processes

PM Specification depends on thermal behavior & mounting uncertainty, leaving < ~8 nm rms for total manufactured SFE.

- **Monolithic PMA** *10 nm rms surface*
  - **Thermal** *5 nm rms*
  - **Polishing** *7.1 nm rms*
  - **Gravity/Mount** *5 nm rms*

Note: Divide by 2 to convert from Wavefront to Surface Error

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Primary Mirror Total Surface Figure Requirement

If the PM is segmented, it still must have < 10 nm rms surface.

Segmenting increases complexity and redistributes errors.

- **Segmented PMA** *10 nm rms surface*
  - **Thermal** *5 nm rms*
  - **Polishing** *5 nm rms*
  - **Segment Phasing** *5 nm rms*
  - **Gravity/Mound** *5 nm rms*

Notes:

Polishing specification is for individual segments.

Phasing specification is how well individual segments can be aligned before correction by a segmented deformable mirror.

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Primary Mirror Total Surface Figure Requirement

Regardless whether monolithic or segmented,

PM must have < 8 nm rms surface figure error (SFE)

And, if segmented, it must have a ‘phased’ wavefront which has same performance as a monolithic aperture.

Next question is how to partition the PM SFE error.

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Spatial Frequency vs Science

Low spatial frequency specification is driven by General Astrophysics (not Exoplanet) science.

Exoplanet instruments have deformable mirrors to correct low-spatial errors and General Astrophysics instruments typically do not.

Mid/High spatial frequency specification is driven by Exoplanet because of ‘leakage’ or ‘frequency folding’.

For exoplanet, the spatial band is from the inner working angle (IWA) to approximately 3X the outer working angle (OWA).

Theoretically, a 64 x 64 DM can correct spatial frequencies up to 32 cycles per diameter (N/2), therefore, the maximum mid-spatial frequency of interest is ~ 90 cycles.

Since mirrors are smooth & DM controllability rolls-off near N/2 limit, a conservative lower limit is ~N/3 or ~20 cycles.

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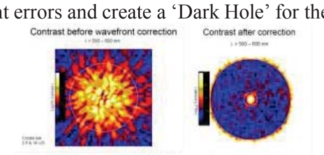
Spatial Frequency vs Exoplant Science

Exoplanet Science requires a Deformable Mirror (DM) to correct wavefront errors and create a ‘Dark Hole’ for the coronagraph.



To image an exoplanet, ‘dark hole’ needs to be below 10^{-10}

Mid-spatial frequency errors move light from core into ‘hole’

DM moves that light back into the core.

High-spatial errors (3X OWA) ‘fold’ or ‘scatter’ light into ‘hole’

Errors above DM range produce speckles whose amplitude varies as $1/\lambda^2$

Krist, Trauger, Unwin and Traub, “End-to-end coronagraphic modeling including a low-order wavefront sensor”, SPIE Vol. 8422, 844253, 2012; doi: 10.1117/12.927143
Shaklan, Green and Palacios, “TPFC Optical Surface Requirements”, SPIE 626511-12, 2006.

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PM SFE Spatial Frequency Specification

Shaklan shows that a UVOIR mirror similar to Hubble (6.4 nm rms) or VLT (7.8 nm rms) can meet the requirements needed to provide a < 10^{-10} contrast 'dark hole'.

- If PM is conjugate with the DM, then PM low-order errors are compensated by DM.
- Recommends < 4 nm rms above 40 cycles
- Both HST & VLT surface figure error is so small enough that there is negligible Contrast reduction from frequency folding
- Because VLT is larger, stiffer and not light-weighted, it is actually smoother at frequencies of concern

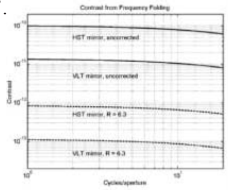


Figure 7. Contrast from frequency folding for spatial frequencies above 48 cycles per aperture, for an 8-m VLT primary and the 2.4 m HST primary. The uncompensated effect is above the required level of 10^{-12} for both mirrors. The sequential DM configuration provides about ~100x reduction of the contrast when it compensates the center of a 100 nm bandpass centered at 633 nm. Both mirrors are acceptable after compensation. The frequency folding effect can be perfectly compensated by the Michelson configuration and is not present in the Visible Nuller.

Shaklan, Green and Palacios, "TPFC Optical Surface Requirements", SPIE 626511-12, 2006.
Shaklan & Green, "Reflectivity and optical surface height requirements in a coronagraph", Applied Optics, 2006 37

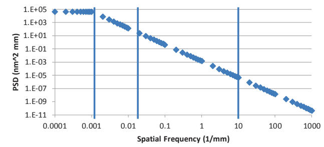
PM Manufacturing Specification

Define band-limited or spatial frequency specifications

Figure/Low	(1 to SF1 cycles/aperture)
Mid Spatial	(SF1 to SF2 cycles/aperture)
High Spatial	(SF2 cycles/aperture to 10 mm)
Roughness	(10 mm to < 1 micrometer)

Assume that Figure/Low Frequency Error is Constant

Key questions is how to define SF1 and SF2



Also, what is proper PSD Slope

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Primary Mirror Spatial Frequency Specification

Manufacturing processes typically range from -2.0 to -2.5 (in special cases to -3.0). Different slopes result in different allocations of PM spatial frequency surface figure error.

Spatial Frequency Band Limited Primary Mirror Surface Specification			
PSD Slope	- 2.0	- 2.25	- 2.5
Total Surface Error	8.0 nm rms	8.0 nm rms	8.0 nm rms
Figure/Low Spatial (1 to 4 cycles per diameter)	5.2 nm rms	5.5 nm rms	5.8 nm rms
Mid Spatial (4 to 60 cycles per diameter)	5.8 nm rms	5.6 nm rms	5.4 nm rms
High Spatial (60 cycles per diameter to 10 mm)	1.4 nm rms	1.0 nm rms	0.7 nm rms
Roughness (10 mm to < 0.001 mm)	0.6 nm rms	0.3 nm rms	0.2 nm rms

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Wavefront Error Stability Specification

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Primary Mirror Surface Figure Error Stability

Independent of Architecture (Monolithic or Segmented), any drift in WFE may result in speckles which can produce a false exoplanet measurement or mask a true signal.

WFE can vary with time due to the response of optics, structure and mounts to mechanical and thermal stimuli.

- Vibrations can be excited from reaction wheels, gyros, etc.
- Thermal drift can occur from slew changes relative to Sun

REQUIREMENT: ΔWFE < 10 pico-meters per 10 minutes

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Primary Mirror Surface Figure Error Stability

Per Krist, once a 10^{-10} contrast dark hole has been created, the corrected wavefront phase must be kept stable to within a few picometers rms between science exposures to maintain the instantaneous (not averaged over integration time) speckle intensity to within 10^{-11} contrast.

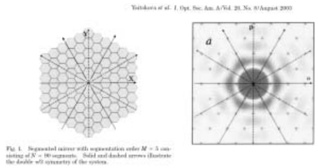
Krist, Trauger, Unwin and Traub, "End-to-end coronagraphic modeling including a low-order wavefront sensor", SPIE Vol. 8422, 844253, 2012; doi: 10.1117/12.927143
Lyon & Clampin, "Space telescope sensitivity and controls for exoplanet imaging", Optical Engineering, Vol 51, 2012; 011002-2 42

Tip/Tilt Errors

A segmented aperture with tip/tilt errors is like a blazed grating removes energy from central core to higher-order peaks.

If the error is ‘static’ then a segmented tip/tilt deformable mirror should be able to ‘correct’ the error and any residual error should be ‘fixed-pattern’ and thus removable from the image.

But, if error is ‘dynamic’, then higher-order peaks will ‘wink’.



Yaitskova, Dohlen and Dierickx, “Analytical study of diffraction effects in extremely large segmented telescopes”, JOSA, Vol.20, No.8, Aug 2003.

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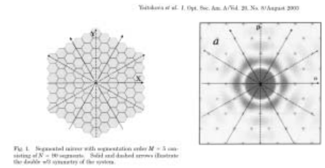
Co-Phasing Errors

Co-Phasing errors introduce speckles.

If the error is ‘static’ then a segmented piston deformable mirror should be able to ‘correct’ the error and any residual error should be ‘fixed-pattern’ and thus removable from the image.

But, if error is ‘dynamic’, then speckles will move.



Yaitskova, Dohlen and Dierickx, “Analytical study of diffraction effects in extremely large segmented telescopes”, JOSA, Vol.20, No.8, Aug 2003.

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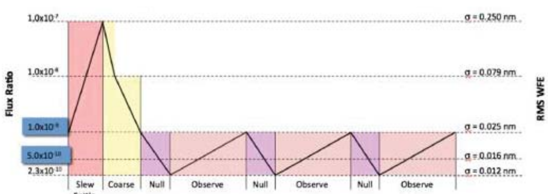
Primary Mirror Surface Figure Error Stability

If the telescope system cannot be designed near zero stability, then the WFE must be actively controlled.

Assuming that DMs can perfectly ‘correct’ WFE error once every ‘control period’, then the Telescope must have a WFE change less than the required ‘few’ picometers between corrections.



Lyon and Clampin, “Space telescope sensitivity and controls for exoplanet imaging”, Optical Engineering, Vol 51, 2012; 011002-2

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Co-Phasing Stability vs Segmentation

Per Guyon:

- Co-Phasing required to meet given contrast level depends on number of segments; is independent of telescope diameter.
- Time required to control co-phasing depends on telescope diameter; is independent of number of segments.
  - To measure a segment’s co-phase error takes longer if the segment is smaller because there are fewer photons.
  - But, allowable co-phase error is larger for more segments.

TABLE 1: Segment cophasing requirements for space-based telescopes (wavefront sensing done at λ=550nm with an effective spectral bandwidth $\delta\lambda$= 100 nm)

Telescope diameter (D) & λ	Number of Segments (N)	Contrast	Target	Cophasing requirement	Stability timescale
4 m, 0.55 µm	10	1e-10	m_V=8	2.8 pm	22 mn
8 m, 0.55 µm	10	1e-10	m_V=8	2.8 pm	5.4 mn
8 m, 0.55 µm	100	1e-10	m_V=8	8.7 pm	5.4 mn

Guyon, “Coronagraphic performance with segmented apertures: effect of cophasing errors and stability requirements”, Private Communication, 2012.

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Controllability Period

Key issue is how long does it take to sense and correct the temporal wavefront error.

Constraining factors include:

Aperture Diameter of Telescope
‘Brightness’ of Star used to sense WFE
Spectral Bandwidth of Sensing
Spatial Frequency Degrees of Freedom being Sensed
Wavefront Control ‘Overhead’ and ‘Efficacy’

Another factor is the difference between systematic, harmonic and random temporal WFE.

The consensus requirement is < 10 pm per 10 minutes.

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Controllability Period

Krist (Private Communication, 2013): wavefront changes of the first 11 Zernikes can be measured with accuracy of 5 – 8 pm rms in 60 – 120 sec on a 5th magnitude star in a 4 m telescope over a 500 – 600 nm pass band (reflection off the occulter). This accuracy scales proportional to square root of exposure time or telescope area.

Lyon (Private Communication, 2013): 8 pm control takes ~64 sec for a Vega 0th mag star and 500 – 600 nm pass band [10^8 photons/m^2-sec-nm produce 4.7 x 10^5 electrons/DOF and sensing error ~ 0.00073 radians = 64 pm at λ= 550 nm]

Guyon (Private Communication, 2012): measuring a single sine wave to 0.8 pm amplitude on a Magnitude V=5 star with an 8-m diameter telescope and a 100 nm effective bandwidth takes 20 seconds. [Measurement needs 10^{11} photons and V=5 star has 10^6 photons/m2-sec-nm.] BUT, Controllability needs 3 to 10 Measurements, thus stability period requirement is 10X measurement period.

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Wavefront Stability

There are 2 primary source of Temporal Wavefront Error:

Thermal Environment

Mechanical Environment

Wavefront Stability - Thermal

Changes in orientation relative to the Sun changes the system thermal load. These changes can increase (or decrease) the average temperature and introduce thermal gradients.

In response to the 'steady-state' temperature change, variations in the Coefficient of Thermal Expansion (CTE) distribution cause static wavefront errors.

Stability errors depend on the temporal response of the mirror system to the thermal change.

Requirement is for WFE to change by < 10 pm per 10 minutes

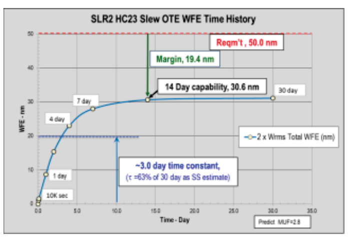
For a low CTE material (< 10 ppb) such as ULE or Zerodur, this requires a thermal drift of < 0.001K per 10 minutes.

For a high CTE material (< 10 ppm) such as SiC, this requires a thermal drive of < 0.000001K per 10 minutes.

Wavefront Stability - Thermal

For example, (while not designed for a UVOIR Exoplanet Science Mission) JWST experiences a worst-case thermal slew of 0.22K which results in a 31 nm rms WFE response.

It takes 14 days to 'passively' achieve < 10 pm per 10 min



13-JWST-0207 F, 2013

Wavefront Stability - Mechanical

Mechanical disturbances

- from spacecraft such as reaction wheels or mechanisms, or
- from the solar wind

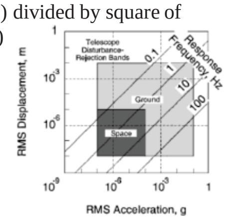
can excite modal vibration modes.

Per Lake, rms wavefront error is proportional to rms magnitude of the applied inertial acceleration (a_{rms}) divided by square of the structure's first mode frequency (f_0)

$$WFE_{rms} \sim a_{rms}/f_0^2$$

To achieve < 10 pm rms requires

First Mode Frequency	RMS Acceleration
10 HZ	< 10^-9 g
100 HZ	< 10^-7 g



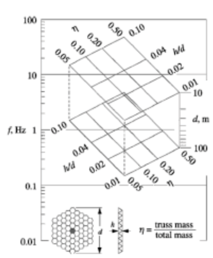
Lake, Peterson and Levine, "Rationale for defining Structural Requirements for Large Space Telescopes", AIAA Journal of Spacecraft and Rockets, Vol. 39, No. 5, 2002.

Wavefront Stability - Mechanical

One way to gain mechanical wavefront stability is to make the system stiffer. A 2X increase has a 4X benefit.

For a Truss Mirror support where Truss Mass = PM Substrate Mass.

Diameter	Depth	f_0
10 m	0.2 m	10 Hz
10 m	2.0 m	100 Hz
20 m	0.4 m	10 Hz
20 m	4.0 m	100 Hz



Note: Adding Stiffness requires MASS.

Another way is to increase isolation.

A final way is active control.

Lake, Peterson and Levine, "Rationale for defining Structural Requirements for Large Space Telescopes", AIAA Journal of Spacecraft and Rockets, Vol. 39, No. 5, 2002.

Wavefront Stability - Mechanical

For example, (while not designed for a UVOIR Exoplanet Science Mission) JWST has several mechanical modes:

- PMA Structure has a ~ 40 nm rms 'wing-flap' mode at ~15 HZ
- Individual PMSAs have a ~ 20 nm rms 'rocking' mode at ~ 40 Hz

Because of the frequency of these modes, to perform Exoplanet Science, their amplitude needs to be reduced to < 10 pm rms.

JWST engineers (private conversation) believe that they could reduce both of these modes to the required < 10 pm rms via the combination of 3 design elements:

1. Operating at 280K instead of < 50K adds dampening
2. Returning Structural Mass removed for 50K operation
3. 120 db of Active Vibration Isolation

Summary Science Driven Specifications

Telescope Performance Requirements

Science is enabled by the performance of the entire Observatory: Telescope and Science Instruments.

Telescope Specifications depend upon the Science Instrument.

Telescope Specifications have been defined for 2 cases:
- 8 meter Telescope with an Internal Masking Coronagraph
- 8 meter Telescope with an External Occulter

WFE Specification is before correction by a Deformable Mirror

WFE/EE Stability and MSF WFE are the stressing specifications

AMTD has not studied the specifications for a Visible Nulling Coronagraph or phase type coronagraph.

8m Telescope Requirements for use with Coronagraph

On-axis Monolithic 8-m Telescope with Coronagraph		
Performance Parameter	Specification	Comments
Maximum total system rms WFE	38 nm	Diffraction limit (80% Strehl at 500 nm)
Encircled Energy Fraction (EEF)	80% within 16 mas at 500 nm	HST spec, modified to larger aperture and slightly bluer wavelength Vary < 5% across 4 arcmin FOV
EEF stability	<2%	JWST
Telescope WFE stability	< 10 pm per 600 sec	
PM rms surface error	5 - 10 nm	
Pointing stability (jitter)	~2 mas	scaled from HST Guyon: ~ 0.5 mas determined by stellar angular diameter.
Mid-frequency WFE	< 4 nm	

8m Telescope Requirements for use with Coronagraph

On-axis Segmented 8-m Telescope with Coronagraph		
Performance Parameter	Specification	Comments
Maximum total system rms WFE	38 nm	Diffraction limit (80% Strehl at 500 nm)
Encircled Energy Fraction (EEF)	80% within 16 mas at 500 nm	HST spec, modified to larger aperture & bluer wavelength Vary < 5% across 4 arcmin FOV
EEF stability	<2%	JWST
WFE stability	< 10 pm per 600 sec	
Segment gap stability	TBD	Soummer, McIntosh 2013
Number and Size of Segments	TBD (1 – 2m, 36 max)	Soummer 2013
Segment edge roll-off stability	TBD	Sivaramakrishnan 2013
Segment co-phasing stability	4 to 6 pm per 600 secs	Depends on number of segments
Pointing stability (jitter)	~2 mas	scaled from HST Guyon, ~ 0.5 mas floor determined by stellar angular diameter.

8m Telescope Requirements for use with Occulter

On-axis Segmented 8-m Telescope with External Occulter		
Performance Parameter	Specification	Comments
Maximum total system rms WFE	38 nm	Diffraction limit (80% Strehl at 500 nm)
Encircled Energy Fraction (EEF)	80% within 16 mas at 500 nm	HST spec, modified to larger aperture & bluer wavelength Vary < 5% across 4 arcmin FOV
EEF stability	<2%	JWST
WFE stability	~ 35 nm	Depends on number of segments
Segment gap stability	TBD	Soummer, McIntosh 2013
Number and Size of Segments	TBD (1 – 2m, 36 max)	Soummer 2013
Segment edge roll-off stability	TBD	Sivaramakrishnan 2013
Segment co-phasing stability	TBD	Soummer, McIntosh 2013
Pointing stability (jitter)	~2 mas	scaled from HST

Conclusions

Conclusion

AMTD is using a Science Driven Systems Engineering approach to develop Engineering Specifications based on Science Measurement Requirements and Implementation Constraints.

Science requirements meet the needs of both Exoplanet and General Astrophysics science.

Engineering Specifications are guiding our effort to mature to TRL-6 the critical technologies needed to produce 4-m or larger flight-qualified UVOIR mirrors by 2018 so that a viable mission can be considered by the 2020 Decadal Review.

Engineering Specification is a 'living' document.

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